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Investigation Into Open-Ended Fitness Landscape Through Evolutionary Logical Circuits

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Cumulative cultural evolution is what made humanity to thrive in various ecological and demographic environments. Solutions to the tasks that humans needed to solve could be mapped onto a task space which could take the form of either closed or open-ended fitness landscape, with the former being modeled more extensively than the latter in studies of cultural evolution. In this article, we modified a simulation by Arthur and Polak (2006) that modeled open-ended fitness landscape by using a computer simulation that builds logical circuits with circuits that were built in earlier trials. We used this simulation to clarify the nature of open-ended fitness landscape and to investigate whether the speed of accumulation of culture is increased by an increase in group size. The results indicated that group size increased the speed of accumulation but is limited than expected. Also, when two types of accumulation, invention and improvement, were distinguished the nature of the two differed. In improvement, the trajectory followed a convex function with productivity of one agent decreasing as group size increased. In invention, the trajectory showed a continuous pattern of rapid increase followed by a plateau.

Keywords
cultural evolution, open-ended fitness landscape, group size, technology s-curve, innovation

Introduction

The accumulation of culture over many generations, or cumulative cultural evolution (Arthur, 2009; Basalla, 1988; Henrich, 2017; Mesoudi, 2011), has led the *Homo* genus to thrive in many, if not all, regions of our planet. Theoretical and empirical investigations into cumulative cultural evolution have paid special interest in the cognitive abilities and the impact of demography (Dean et al., 2013; Henrich, 2004). Although not as frequent, there exist another interest in the fitness landscape (also called adaptive landscape or design space) of cumulative cultural evolution (Acerbi et al., 2015; Miton & Charbonneau, 2018). Fitness landscape refers to a set of all potential solutions to a task that agents may produce (Miton & Charbonneau, 2018).

Fitness landscapes could be modeled in two different ways. One that is used above and in most studies of cumulative cultural evolution is *closed* fitness landscape. Closed fitness landscape refers to a fitness landscape that cannot be altered by the decisions or the actions of an agent solving a task. This implies that all the choices in the fitness landscape can be chosen at any time period. For example, Mesoudi and O'Brien (2008) created a fitness landscape that consisted of 4 dimensions (width, height, thickness, and shape), which was used to create a virtual arrowhead. Each dimension was designed with a particular fitness function so that each coordinate in the dimension corresponded to a particular fitness. Participants in their experiment changed the coordinates in each dimension to achieve the largest fitness or calories. Closed fitness landscapes are useful because they are easy to formulize. On the other hand, it also gives participants the opportunity to find the maximum fitness in the early stages of transmission by mere chance.

In contrast, *open-ended* fitness landscape refers to a situation where an accumulation opens up a new landscape for selection to operate. As a result, these cultural evolutionary systems tend to increase in complexity not only because the fitness landscape tend to increase in space, but also these newly opened fitness landscapes can replace the highest peak in the fitness distribution (Clark 1985; Arthur 2009; Solé et al., 2002). Usually, the complexity is increased by recombining already created artifacts together to create new ones, which captures the essence of technological evolution (See SI:1 for examples). Derex and Boyd (2016) for instance found experimentally that in an open-ended fitness landscape, increase in group size alone will not increase the chance of finding the optimal solution which built upon the idea formally believed in cultural evolution studies.

Another experiment aimed at modelling the nature of technological evolution by simulating the evolution of logical circuits. Arthur and Polak (2006) simulated a situation where an agent randomly wired together logical circuits to create new circuits. They differentiated newly made circuits by improvement and invention where the former implying circuits that improved preexisting circuits that were made previously and the latter implying circuits that served a new purpose. Logical circuits have a characteristic where key circuits such as AND circuit or OR circuit be used to create diverse number of other functional circuits (see SI:2 for more details). Whenever such inventions were made, these opened newly fitness landscapes that either made previously created circuits more efficient (termed gales of destruction; Schumpeter,

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1911) or made newly inventions be invented rapidly (termed technological Cambrian explosion).

This study was able to model open-ended fitness landscape by actually modelling technology that is often invented in industries. Considering technological evolution often modeled in cultural evolutionary studies lack external validity (Miton & Charrboneau, 2018), models made by Arthur and Polak (2006) could be used to test the theories that were already created in cultural evolution studies in closed fitness landscape.

In the present study, we attempt to further clarify the feature of open-ended fitness landscape by varying group size in the model created by Arthur and Polak (2006). We added conditions where agents in the same society were able to use circuits built by other agents. Just as in Derex and Boyd (2016), we were interested in how various group sizes perform in an open-ended fitness landscape created by Arthur and Polak (2006). Since the present study have no transmission error, we are not particularly concerned about whether increase in group size stop the deterioration of cumulative culture. Additionally, by using Arthur and Polak (2006) simulation, we may be able to see whether group size have different effect on invention and improvement. In the following simulation, agents in the same trial did not interact with one another that could create a synergetic interaction for simplicity.

Method

The simulation was a modified version of Arthur and Polak (2006). In the original simulation, several NAND circuits were randomly wired together in a non-cyclic way to make a new circuit that could be used to create another circuit in further trials. This sequence was repeated several thousand times, which created circuits that were often used in reality (e.g. OR circuit, AND circuit, and n-bit ADDER). The simulation used in this experiment added agents that created circuits simultaneously to vary group size.

In the first trial of all conditions, agent(s) started only with a NAND circuit. Agents wired several NAND circuits to create a new circuit that served a new functionality. The minimum and the maximum number of total NAND circuits that could be wired together were 2 and 12 respectively throughout the trials. The new circuit that was created in the first trial was automatically stored in the pool, which was a group of circuits that could be used as a component for making a new circuit in further trials. Each circuit was insured to be a directed acyclic graph. The choice of using which preexisting circuit was determined by a choice function (Arthur and Polak, 2006; SI:2) that specifies probabilities of selection.

Circuits were evaluated by its functionality, i.e. truth table. Preceding the simulations, goals were defined which consisted of specific input-output circuitry (Table 1; SI:3). When the created circuit either met the goal for the first time or was close to meeting the goal determined by the prespecified truth table, the created circuit was called *invention*.

Determined by the truth table, when the created circuit met the same functionality as with the circuit that was included in the pool but with less cost (here cost refers to the total number of NAND circuits used since all the created circuits are created from NAND circuits), the created circuit was called *improvement*. When improvement was made, the older circuit that fulfilled the same functionality was deleted from the pool. On the other hand, if the circuit was neither an invention or an improvement, the circuit was called *junk* and was never included in the pool.

The conditions were separated by how many agents were involved in creating the circuits in the simultaneous trial. The group sizes were 1, 2, 4, and 8. In the conditions that had multiple agents, agents created circuits by themselves. After creating the circuits, the circuits were pooled together. The pooled circuits could be used by all agents in the next trial. This meant that the agents had no synergetic influence on one another.

In each condition, 1 replication consisted of 100,000 trials and 20 replications were run. Whenever all the goals were met, the replication was terminated. The program was created in GNU CLISP (ver. 2.49) which is an implementation of Common Lisp. The simulation was run on 16GB memory Windows 10.

Table 1. Goals that were defined preceding the simulations.

There were 16 goals in total. N-bit adder had a range of 1 to 8.

Name	Inputs	Outputs
NOT	1	1
IMPLY	2	1
AND	2	1
OR	2	1
XOR	2	1
EQUIV	2	1
3-WAY-AND	3	1
FULL-ADDER	3	2
n-BIT-ADDER	$2n$	$n+1$

Results

The number of trials by conditions and replications are shown in Table 2. Replications were terminated when all the given goals had been achieved. Replication 16 of group size 4 was aborted by memory error, thus we excluded it from the following results. Since the main results are on inventions and improvement, results for goals and junks are in SI:4.

Basic properties of evolution in group size-1

Since the results of size-1 condition were identical to Arthur and Polak (2006), we regarded the results of size-1 condition as a baseline. The primary results of group size-1 are shown in Figure 1.

The number of inventions in each trial is shown in figure 1a. Generally, we saw a repeated pattern where there was a rapid increase in invention followed by a period where there was minimal increase, which resembled that of a continuous convex function. This continuous sigmoidal like pattern was present in all replication.

Figure 1b shows the number of improvements that made the circuit more efficient. In total, we saw a general

Table 2. The number of trials by conditions and replications.

Replications were terminated automatically when all prespecified goals were met. Dashed data represents the data that was terminated due to error.

	Conditions			
Replication	size-1	size-2	size-4	size-8
1	100,000	100,000	95,950	42,000
2	100,000	100,000	58,000	75,216
3	100,000	100,000	100,000	53,636
4	100,000	100,000	88,867	51,952
5	100,000	100,000	100,000	38,965
6	100,000	100,000	100,000	57,881
7	100,000	97,981	100,000	37,000
8	100,000	100,000	90,000	62,796
9	100,000	100,000	100,000	66,986
10	100,000	100,000	68,988	38,100
11	100,000	90,974	93,754	44,977
12	100,000	100,000	79,970	66,716
13	100,000	100,000	100,000	44,000
14	100,000	100,000	100,000	56,974
15	100,000	100,000	75,949	59,000
16	100,000	100,000	~~25,965~~	49,989
17	100,000	100,000	79,399	38,717
18	100,000	100,000	83,987	77,000
19	100,000	100,000	64,000	44,617
20	100,000	100,000	100,000	46,772

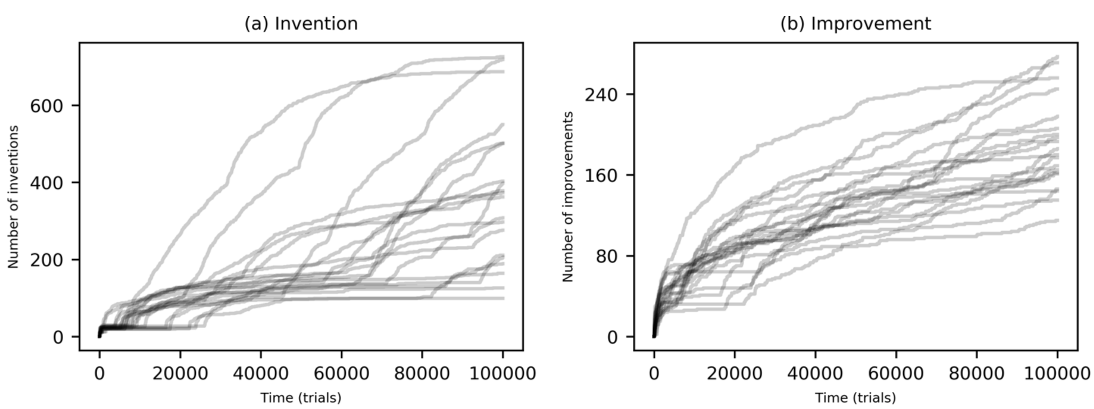

Figure 1. The cumulative score for each variable in group size-1.

Cumulative score for each replication in group size-1. (a) represents the results from invention and (b) represents the results from improvement.

increase in improvements as trials progress. Though in some replications we saw a repeated convex like shape in the increase in improvement, compared to invention however, the pattern was not robust.

Comparison between group sizes

Figure 2 shows the comparison within invention. The average number of inventions indicated that as group size increased, cumulative increase in invention started to resemble that of a repetitive sigmoidal shape. This indicated that as group size increased, the gentle slope seen in replications under group size-1 was quickly followed by a rapid increase. And as quicker the goals were met, the plateau in bigger group sizes became longer along the end of the simulation. Since this simulation had no synergetic interaction between agents, effects of group size n should be homologous to speeding up the trials by n. Figure 2b shows the difference between speeding up the trials in group size 1 by n times compared to the actual data. Similar to goals, the light line was above the solid line

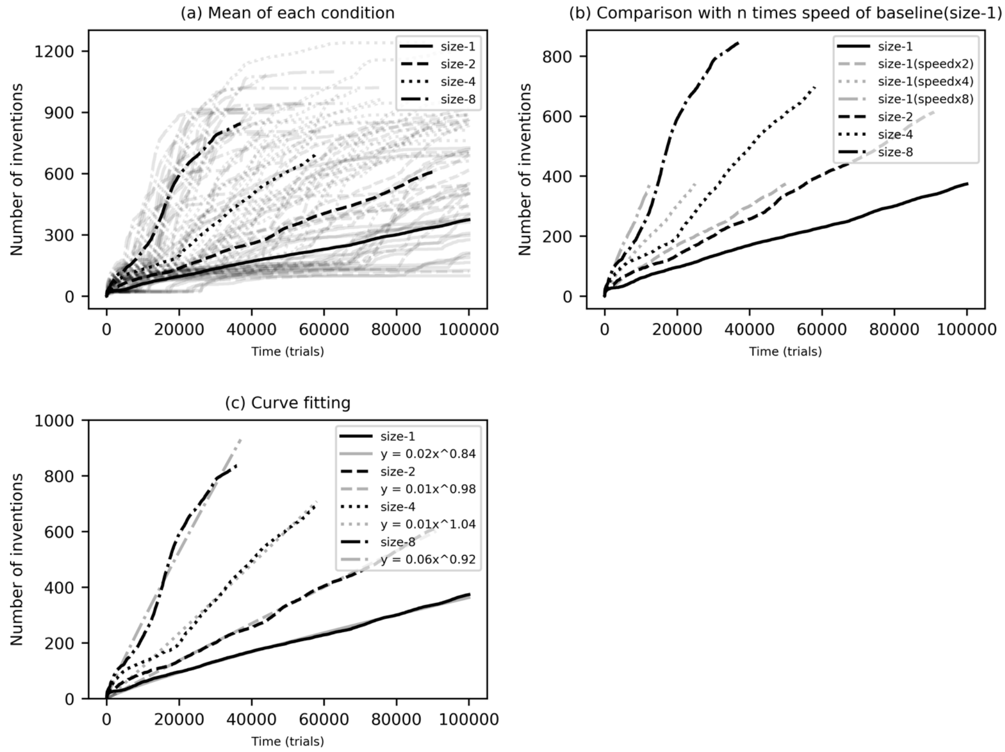

Figure 2. The cumulative score for invention in each condition.

(a) Light lines indicate raw data from each replication. Solid lines indicate the average. The average value was displayed up to a point where no termination was present in all trials. (b) Solid lines represent the average cumulative score. Light lines represent the prediction calculated with group-size 1. (c) Solid lines represent the average cumulative score. Light lines represent the fitted line using power-law function.

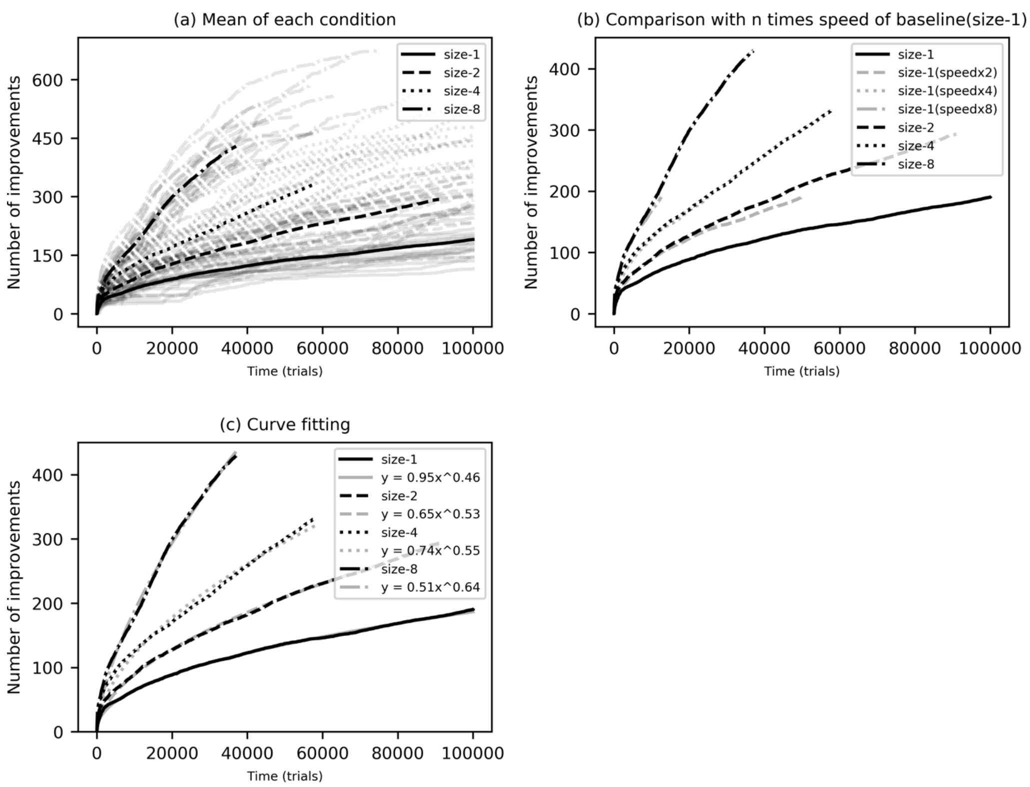

Figure 3. The cumulative score for improvement in each condition.

(a) Light lines indicate raw data from each replication. Solid lines indicate the average. The average value was displayed up to a point where no termination was present in all trials. (b) Solid line represents the average cumulative score. Light lines represent the prediction calculated with group-size 1. (c) Solid lines represent the average cumulative score. Light lines represent the fitted line using power-law function.

indicating that the productivity of group size was lower than expected. We also fitted the data using OLS with the power function applied through the curve_fit function from SciPy (ver. 1.2.1) module in Python (ver. 3.6.8). Since the data fitted poorly in invention, it suggested that the increase in invention did not follow a power function and those follow a more sophisticated one.

Figure 3a shows the actual data and their average results from improvement in each condition. Consistent with inventions, speed of improvements also increased with increase in group size similar to a gentle upward convex function. When the speed of group size-1 was increased to be compared with other group sizes, the two lines seemed to overlap with one another. This indicated that the speed of improvements was proportional to that of group size. Just as in invention, we fitted the data with OLS. The results indicated that improvement was roughly proportional to the square root times the group size, but there was a pattern in which the estimated value of the index increased as the group size increased. This suggested that as the group size increased, the rate of increase of the slope became steeper. The results from OLS also suggested that the properties of invention and improvement differed. We compared the normalized RMSE (Root Mean Squared Error) from the OLS between invention and improvement in Figure 4. This suggested that improvement fit well with the OLS more than invention indicating that the nature of the two differed.

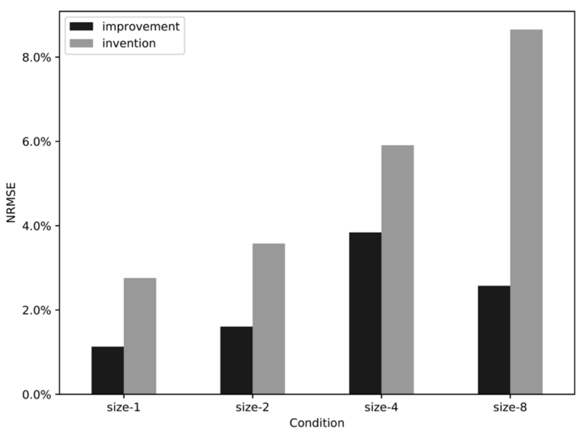

Figure 4. Comparison of normalized RMSE from the fitted model in all condition.

Bar graph representing the normalized RMSE (Root Mean Squared Error) from the curve fit model between invention and improvement.

Discussion

Open-ended fitness landscape is one of the features of technological evolution. However, the nature of this aspect is understudied especially in fields like cultural evolution where many have pointed out the mechanisms that facilitate the growth in technology under a closed fitness landscape. The main goal of this study was to examine the architecture of open-ended fitness landscape through the evolution of logical circuits with varying group sizes, which is one of the mechanisms identified as the cause of cumulative cultural evolution (Henrich, 2004; Henrich, 2017).

Results showed that the increase in speed of invention by increase in group size was lower than the baseline (which was the n-times the speed of group size-1) and the way that inventions accumulated were similar to a repetitive sigmoidal function. On the other hand, improvement matched that of the baseline and the rate in which improvement increased was square root times the group size, which means that the effect of group size becomes smaller as group size becomes bigger.

Looking further into the comparison between the baseline and the actual result of varying group size in invention, the actual data seems to catch up on the baseline after a few trials. Since invention in logical circuits needs simpler circuits to be invented beforehand, there is a bottleneck before any further inventions can be made. This may indicate that in an open-ended fitness landscape where new fitness landscape opens hierarchically, group size will only be an advantage only after a few fitness landscapes have been opened.

One reason for the decrease in the effect of group size in improvement could be due to a chance that one of the agents in the group created an improvement so efficient that other agents could not improve any further. The chance that any agent creates an efficient circuit increase as group size increase, which is similar to the point seen in Henrich (2004).

The interesting finding is that the function of invention and improvement differed. Kaufmann (1993) has argued that when agents start to hill climb in closed fitness landscape, the probability that the agent can climb further decreases as she reaches the top. This would be an explanation for marginally decreasing function in improvement. In invention, we observed an s-shaped curve, which could be seen in many field research (Foster 1986; Christensen 1997; Christensen 2009). As mentioned by Arthur and Polak (2006), the rapid take-off of invention is subject to goals (e.g. AND circuit, OR circuit, etc.) being met. This means that when a goal is met, inventions using that goal circuit rapidly increase. However, at some point, the limits of using that goal circuit are reached and the growth of inventions stops. Such a result was never reported in cultural evolutionary models and can be considered as a key finding in this study. Nonetheless, since this is a post hoc analysis, whether or not the results that inventions take the form of a repetitive s-curve is open for debate.

Besides the difference between invention and improvement, one of the take-home messages is that even if group size increases, the productivity of one agent being added decreases as group size becomes bigger. This also suggests that an increase in group size is sufficient to maintain technology but not enough to accelerate the speed of innovations. However, we did not include synergetic interactions for simplicity in this study which means there is still room to argue that with interaction, group size does increase the speed of innovations. On the other hand, behavioral sciences have shown that group processes do not always have a positive effect (e.g. groupthink, social loafing). We need further examination to see whether interaction does increase the speed of innovations in an open-ended fitness landscape.

There are still many candidates that may affect the speed of innovations. One example is network structure (Frenken 2006; Powell, Koput, & Smith-

Doerr, 1996). Derex and Boyd (2016) have reported experimentally that partial connectivity increases the innovations of a group more than a full connected group in an open-ended fitness landscape. Such mechanisms are needed to be explored in future research.

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Author Contributions

The initial research was designed and conducted by M.S. and K.S. K.S. programmed and analyzed the data. M.S and K.S. wrote the manuscript.

Supplementary Information

Supplementary Information (SI) is stored in osf.io/9kzjc

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